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THE IDENTIFICATION OF JADE BY MEANS OF X-RAY DIFFRACTION PATTERNS

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Introduction

Jade is one of the oldest of mineralogical materials used by primitive man. It was used in the construction of hatchets, chisels, and ornaments. Such articles have been found in many localities in North America, Asia, Europe, and New Zealand. The source of the jade found in Europe was for many years unknown, a fact which caused extended controversy concerning the methods of commercial intercourse of pre-historic man. Jade has long been a much prized mineral both for ornamental and religious purposes among the Chinese, its use dating back at least as far as 2852 B.C. Objects, some of which undoubtedly required a life time to carve with a hand drill, have found their way into several large collections. The most notable collection available to the American public is the Bishop Collection in the Metropolitan Museum of Art, New York City.

The historical and archeological aspects of jade have been fully reviewed by Laufer.[1] He has furnished an extensive bibliography dealing with various phases of the subject. An extensive examination of jade has also been made of the Bishop Collection.[2]

Jade has recently shown increasing popularity in the jewelry trade and is now frequently used for necklaces and ornaments of various kinds. In commercial usage the minerals jadeite, chloromelanite, and nephrite are usually included under the name of jade. The characteristic fine grained, dense, or compact nature of these minerals, together with the fact that the specimens may not consist entirely of one mineral, involves problems in identification not always easily solved by ordinary routine methods.

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[1] Laufer, Berthold, Jade: *Field Museum of Natural History,* Publication **154.** *Anthropological Series,* vol. **X,** 1912.

[2] Bishop, Heber R., Investigations and Studies in Jade. *New York,* **1906.** Privately printed. Two Volumes. 98 copies. (Available at the Metropolitan Museum of Art, New York City.)

In view of the extensive advances in x-ray diffraction technique that have been made during the last few years, it is possible, in many instances, to identify fine grained crystalline minerals by comparing their x-ray diffraction patterns with standard patterns. The present investigation is an attempt to utilize such methods of mineral study in an effort to overcome a few of the difficulties involved in the identification of jade. The first problem in such an x-ray diffraction study is to make up a set of standard patterns of known specimens with which the unknown material may be compared. In order to make the study cover a wider range of practical application, several imitations of jade should also be included. A number of specimens of jadeite, chloromelanite, and nephrite as well as imitations such as vesuvianite (californite), serpentine (williamsite), and agalmatolite have been examined by means of x-rays in an attempt to establish a standard set of diffraction patterns. The usual specific gravity and optical determinations have also been made on the specimens. Optical study has included examination of both thin sections and crushed fragments. Several specimens previously analyzed chemically have also been studied optically and by means of x-rays.

The writer is indebted to Professor Paul F. Kerr of Columbia University for suggesting this problem as well as for his assistance and advice during the course of the investigation and the preparation of this paper.

PHYSICAL PROPERTIES

Complete physical data on jade are given in Dana's *System of Mineralogy*. Only a few of the properties especially useful in identification are referred to in this discussion.

Except in the case of those who have unusual experience, the sight identification of jade is often inaccurate because of the extreme variation in texture, color, and quality of the material. The ordinary differences in appearance existing between hand specimens of jadeite and nephrite were pointed out by Clark and Merrill.[3] As a rule, jadeite and its dark green variety chloromelanite are somewhat granular in texture whereas nephrite is more inclined to be compact and fibrous throughout. Such a distinction between the jade minerals, however, is not always reliable.

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[3] Clark, F. W. and Merrill, G. P., On Nephrite and Jadeite: *Proc. U. S. Nat. Mus.*, vol. **XI**, 1888, pp. 115–130.

The jade minerals may be separated more or less satisfactorily on the basis of specific gravity. However, if quartz, albite, various pyroxenes or amphiboles and alteration products, as well as numerous other minerals are present they will materially alter the specific gravity determinations of the three jade minerals. The average specific gravity of 107 samples of jadeite, with a few specimens of chloro melanite, in the Bishop Collection at the Metropolitan Museum of Art was reported by Hallock to be 3.3202.[4]

The average specific gravity of nephrite from the Egleston Museum at Columbia University was determined in this study to be 2.992. Chloromelanite has been reported by Damour to vary from 3.36 to 3.43 in specific gravity.[5] In general, providing the material is pure, the three jade minerals may be distinguished from each other by this method, although some of the imitations might easily be confused. The following table includes determined and reported values of specific gravity for the jade minerals and their imitations.

TABLE I.

	Specific Gravity
Jadeite	3.296
Chloromelanite[6]	3.36–3.43
Nephrite	2.992
Vesuvianite (californite)	3.284
Serpentine (williamsite)	2.638
Agalmatolite	2.631
"South African Jade" (grossularite)[7]	3.33–3.52

OPTICAL PROPERTIES

The most reliable optical constants available for the identification of the jade minerals and their imitations are the indices of refraction. The following table includes values determined during the course of the investigation as well as several determinations recorded in the literature:

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[4] Hallock, W., in H. R. Bishop's Jade Book, vol. **I,** 1906, p. 116.

[5] Damour, A., Nouveaux essais sur la Cholormelanite: *Soc. Fr. de Min.*, Bull. **16,** 1893, pp. 57–59.

[6] Damour, A., Nouveaux essais sur la Cholormelanite: *Soc. Fr. de Min.*, Bull. **16,** 1893, pp. 57–59.

[7] Hall, A. L., On "Jade" (Massive Garnet) from the Bushveld in the Western Transvaal: *S. A. Geol. Soc., Trans. and Proc.*, **27,** 1924, pp. 39–55.

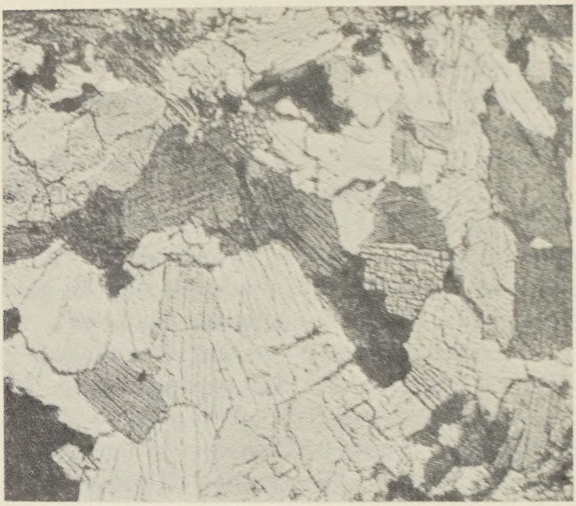

FIG. 1. Photomicrograph of jadeite illustrating the prismatic habit and cleavage, and the granular structure. Crossed nicols. ×27.

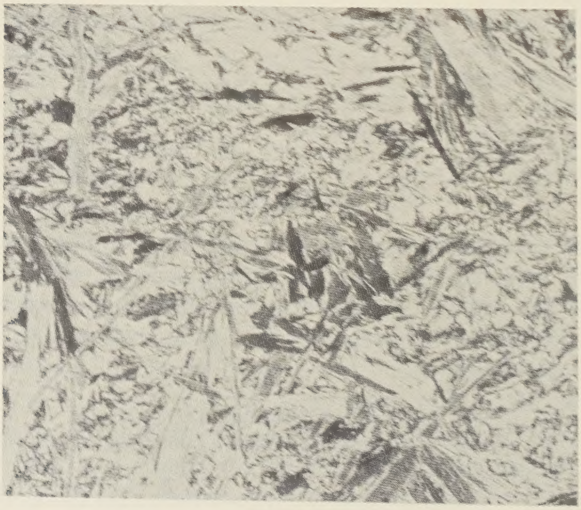

FIG. 2. Photomicrograph of nephrite illustrating the occurrence in long, bladed, radiating fibers. Crossed nicols. ×27.

TABLE II

	α	β	γ	$\gamma-\alpha$
Jadeite (China)	1.650		1.664	.014 (±.003)
Chloromelanite (Burma)	1.653		1.685	.032 (±.003)
Diopside-jadeite[8] (Tuxtla statuette)	1.666	1.674	1.688	.022
Soda Jadeite[8] (Thibet)	1.655	1.659	1.667	.012
Nephrite (Jordansmühl, Silesia)	1.600		1.625	.025 (±.003)
Nephrite[9] (Bahia, Brazil)	1.597		1.625	.028
Tremolite[10] (Lee, Mass.)	1.5992	1.6132	1.6246	.0254
Actinolite[11] (Krageroe, Norway)	1.636		1.660	.024
Serpentine (williamsite) (Texas, Pa.)	1.566		1.574	.008 (±.003)
Vesuvianite (californite) (Siskeyou Co., Calif.)	1.699		1.708	.009 (±.003)
Agalmatolite (China)	1.550		1.578	.028 (±.003)
Grossularite[12] (Western Transvaal)	1.72–1.73 (sometimes doubly refracting)			

Although the examination of jade in thin section is not a practical method of identification, thin sections were examined in order to ascertain the purity of the specimens examined by *x*-ray diffraction methods. Several specimens of each of the jade minerals as well as of the imitations were sectioned and only those samples which proved to be composed of a single mineral were later photographed by *x*-rays. (See Figures 1 and 2.)

Jadeite is colorless in thin section and occurs in granular crystals characterized by distinct prismatic cleavage. Basal sections display two cleavages at nearly right angles. Frequently the material is partially altered to serpentine and uralite. Chloromelanite is similar to jadeite except that it has a distinct greenish cast even in thin section. Nephrite, on the other hand, is composed of fine, compact, frequently radiating aggregates and bundles of fibers and scale-like crystals.

[8] Washington, H. S., The Jadeite of the Tuxtla Statuette: *Proc. U. S. Nat. Mus.*, vol. **60**, 1922.

[9] Washington, H. S., Nephrite Celt from Bahia, Brazil: *Pan-Am. Geol.*, vol. **37**, 1922, pp. 198–202.

[10] Washington, H. S. and Merwin, H. E., Note on Enstatite, Hypersthene, and Actinolite: *Am. Mineral.*, vol. **8**, no. 4, pp. 63–67.

[11] Ford, W. E., A Contribution to the Optical Study of the Amphiboles: *Am. Jour. Sci.*, 4th series, vol. **37**, 1914, pp. 179–193.

[12] Hall, A. L., On "Jade" (Massive Garnet) from the Bushveld in the Western Transvaal: *S. A. Geol. Soc., Trans. and Proc.*, **27**, 1924, pp. 39–55.

X-Ray Diffraction Study

Standard samples of jade were first established by optical and physical means, then x-ray diffraction patterns were taken. The samples were ground to about 350 mesh, from 50 to 100 milligrams of material or even less being found sufficient to give a good pattern. In the case of very fine, granular material it is possible to secure a pattern by reflection from a straight line edge entirely avoiding even slight damage to the specimen. It was found that a sufficient amount of material for x-ray examination could be readily removed from the under side of the base of a carved object with a small drill, resulting in but little damage to the specimen.

The general problems of the pyroxene and amphibole groups materially affect the x-ray study of the jade minerals. Previous x-ray studies of the pyroxenes and amphiboles have been of considerable assistance in establishing standard patterns. A number of crystal structure studies on the pyroxenes and amphiboles are on record which have been carried on by utilizing Laue, x-ray spectrometer, and x-ray diffraction photographs.[13]

An x-ray examination of the pyroxenes by Wyckoff, Merwin and Washington indicated that nearly all of the minerals usually classed as pyroxenes could be classified in four general groups according to their similarities in x-ray diffraction patterns. In the first group were placed diopside, hedenbergite, acmite, jadeite, and augite. The size of the unit cell and the arrangement of the atoms in the lattice were determined from a study of the Laue photographs of single oriented crystals. Wyckoff gives the following measurements for diopside:[14]

$$a=9.71\text{Å};\ b=8.89\text{Å};\ c=5.24\text{Å};\ \beta=74°10'.$$

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[13] Wyckoff, R. W. G., Merwin, H. E., and Washington, H. S., X-ray Diffraction Measurements upon the Pyroxenes: *Am. Jour. Sci.*, 5th series, vol. **10**, 1925, pp. 383–397.

Wyckoff, R. W. G., and Merwin, H. E., The Space Group of Diopside: *Am. Jour. Sci.*, 5th series, vol. **9**, 1925, pp. 379–394.

Warren, B., and Bragg, W. L., The structure of Diopside Ca $Mg(SiO_3)_2$: *Zeit. f. Krist.*, **69**, 1928, pp. 168–193.

Warren, B. E., The Crystal Structure and Chemical Composition of the Monoclinic Amphiboles: *Zeit. f. Krist.*, **72**, 1930, pp. 493–517.

Gossner, B. and Spielberger, F., Chemische und röntgenographische Untersuchungen an Silikaten: *Zeit. f. Krist.*, **72**, 1930, pp. 111–142.

[14] Wyckoff, R. W. G. and Merwin, H. E., The Space Group of Diopside Ca Mg $(SiO_3)_2$: *Am. Jour. Sci.*, 5th series, vol. **9**, 1925, pp. 379–394.

The size of the unit cell for the other pyroxenes has not been calculated but has been compared with that of diopside, the latter being taken as 1.000.[15] The relationship between the relative sizes of the unit cells of jadeite, diopside, and acmite were thus brought out as follows:

TABLE III

Film No.	Acmite	Jadeite
1.	.995	.976
2.	.995	.971
3.	.994	.976
4.	.994	.972
	.9945	.974

Washington has shown that jadeite from the Tuxtla statuette is not a simple jadeite but rather a mixture of the jadeite molecule and the diopside molecule in almost equal proportions. He notes that the jade of Middle America, in contrast to most of that from the Orient, is especially characterized by the presence of diopside in varying but usually large amounts.

It has been pointed out that jadeite occurs in isomorphous mixture with acmite, the ferric iron replacing a portion of the alumina.[16] Chloromelanite is probably a very complex mineral consisting of an isomorphous mixture of jadeite, diopside and acmite.

X-ray diffraction photographs were taken of several samples of jadeite and chloromelanite from the Egleston Museum at Columbia University. All the specimens examined were from China, Thibet or Burma. In order to compare jadeite with the minerals with which it occurs in isomorphous mixtures, *x*-ray diffraction patterns were also made of diopside from Zillerthal, Norway, and acmite from Norway (Fig. 3). The interplanar spacings of the atoms for these minerals were calculated in Angstrom Units ($\times 10^{-8}$ cm.) and corrected by comparison with patterns of sodium chloride. The patterns given by jadeite and chloromelanite proved to be identi-

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[15] Wyckoff, R. W. G., Merwin, H. E., and Washington, H. S., *X*-ray Diffraction Measurements upon the Pyroxenes: *Am. Jour. Sci.*, 5th series, vol. **10**, 1925, pp. 383–397.

[16] Doht, R. and Hlawatsch, C., Über einen ägirinähnlichen Pyroxene und den Krokydolit vom Mooseck bei Golling, Salzburg: *Wein Geol. Reich.*, **1913**, pp. 79–95.

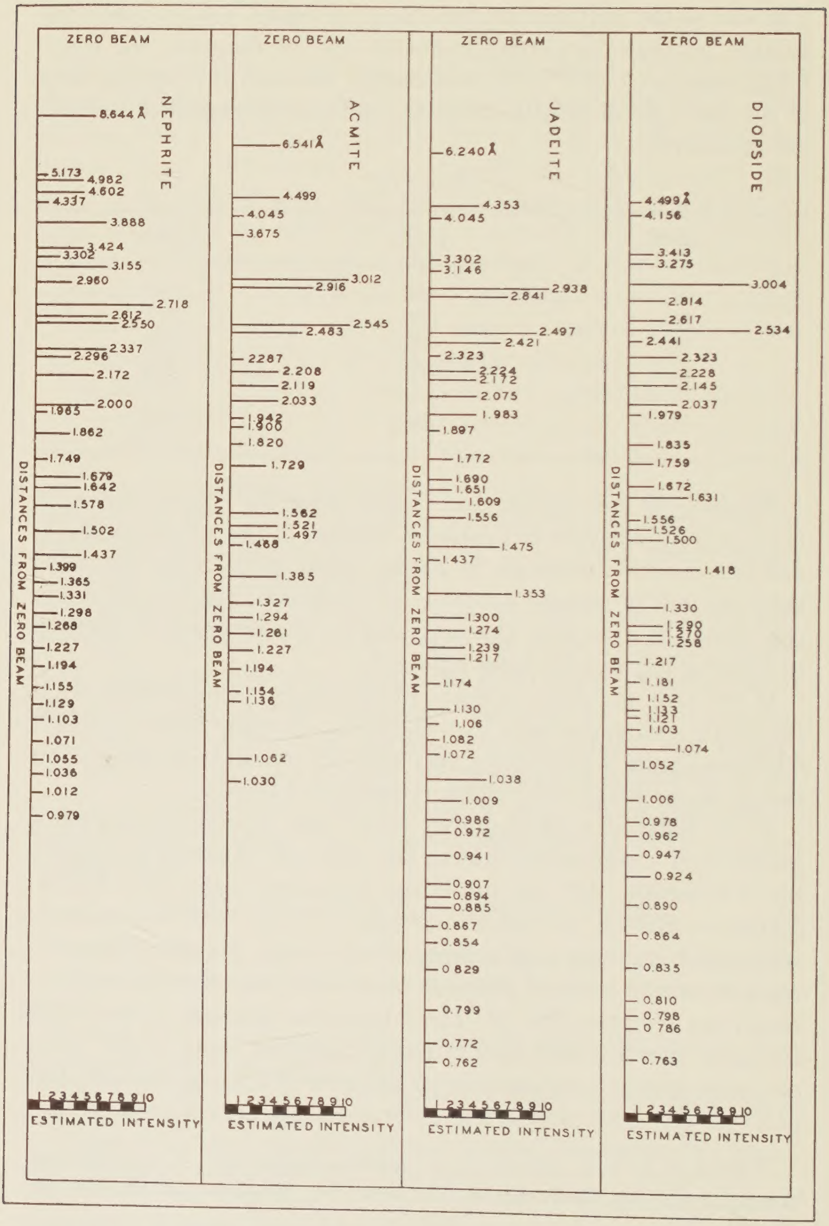

FIG. 3. Chart showing the x-ray diffraction lines of diopside, jadeite, acmite, and nephrite.

cal, but quite distinct from either diopside or acmite, although there is apparently a certain similarity. Sufficient analyzed material was not available for an *x*-ray diffraction study of the effect of the addition of varying amounts of the diopside and the acmite molecules on the interplanar spacing of jadeite.

In the case of the amphibole group, the position of the atoms in the space lattice of tremolite and actinolite have been calculated by Warren from Laue and *x*-ray spectrometer photographs.[17] He calls attention to the close similarity between the size of the unit cells of tremolite and diopside. The unit cells of actinolite and tremolite are practically identical in size.

TABLE IV

Diopside	Tremolite	Actinolite
$a=9.71$Å	$a=9.78$Å	$a=9.8$Å
$b=8.89$Å	$b=17.8$Å	$b=17.9$Å
$c=5.24$Å	$c=5.26$Å	$c=5.27$Å
$\beta=74°10'$	$\beta=73°58'$	

In the case of the amphibole, tremolite, and the pyroxene, diopside, a, c, and β are said by Warren to be nearly identical. In the case of b, however, the value for diopside is about one-half the 17.8Å of tremolite.

X-ray diffraction photographs were taken of several samples of nephrite from New Zealand, China, and Jordansmühl, Silesia. In addition, patterns were obtained of tremolite from Gullsjo, Sweden, and actinolite from Greiner, Tyrol. The patterns given by all of these minerals proved to be identical.

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[17] Warren, B. E., The Crystal Structure and Chemical Composition of the Monoclinic Amphiboles: *Zeit. f. Krist.*, **72**, 1930, pp. 493–518.

Warren, B. E., The Structure of Tremolite $H_2Ca_2Mg_5(SiO_3)_8$: *Zeit. f. Krist.*, **72**, 1929, pp. 42–57.

Table V

X-ray Diffraction Measurements

d in Å

Diopside	Jadeite	Acmite	Nephrite
4.499	6.240	6.541	8.644
4.156	4.353	4.499	5.173
3.413	4.045	4.045	4.982
3.275	3.302	3.675	4.602
3.004	3.146	3.012	4.337
2.814	2.938	2.916	3.888
2.617	2.841	2.545	3.424
2.534	2.497	2.483	3.302
2.441	2.421	2.287	3.155
2.323	2.323	2.208	2.960
2.228	2.224	2.119	2.718
2.145	2.172	2.033	2.612
2.037	2.075	1.942	2.550
1.979	1.983	1.900	2.337
1.835	1.897	1.820	2.296
1.759	1.772	1.729	2.172
1.672	1.690	1.562	2.000
1.631	1.651	1.521	1.965
1.556	1.609	1.497	1.862
1.526	1.556	1.468	1.749
1.500	1.475	1.385	1.679
1.418	1.437	1.327	1.642
1.330	1.353	1.294	1.578
1.290	1.300	1.261	1.502
			1.437
1.270	1.274	1.227	1.399
1.258	1.239	1.194	1.365
1.217	1.217	1.154	1.331
1.181	1.174	1.136	1.298
1.152	1.130	1.062	1.268
1.133	1.106	1.030	1.227
1.121	1.082		1.194
1.103	1.072		1.155
1.074	1.038		1.129
1.052	1.009		1.103
1.006	0.986		1.071
0.978	0.972		1.055
0.962	0.941		1.036
0.947	0.907		1.012
0.924	0.894		0.979
0.890	0.885		
0.864	0.867		

TABLE V (*Continued*)
X-RAY DIFFRACTION MEASUREMENTS
d in Å

Diopside	Jadeite	Acmite	Nephrite
0.835	0.854		
0.810	0.829		
0.798	0.799		
0.786	0.772		
0.763	0.762		

Figure 4 is included in order to show the *x*-ray diffraction patterns of the various imitation jade minerals compared with those of jade. It is apparent that all of the patterns are easily distinguished from each other.[18]

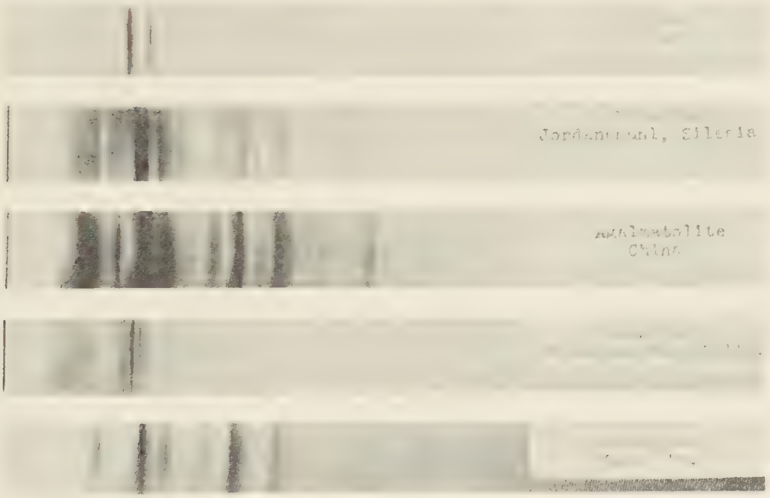

FIG. 4. *X*-ray diffraction patterns of the jade minerals and their common imitations.

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[18] Complete *x*-ray diffraction data on grossularite garnet are given by Agar and Krieger. (*Am. Jour. Sci.*, vol. **24,** July, 1932). Garnet, however, is seldom a convincing imitation of jade even in the case of the well known South African variety.

SUMMARY

Physical, optical, and chemical criteria have heretofore been relied upon exclusively in the identification of the jade minerals and their imitations. The identification is often either uncertain or unduly complicated when limited to these methods. It is suggested therefore, that *x*-ray diffraction patterns might be of assistance in identification. A number of *x*-ray diffraction photographs have been taken for comparative purposes to be used in the identification of jade and the more common imitations. The interplanar spacings of the atoms have been calculated for jadeite, the closely related pyroxenes, diopside and acmite, and also for nephrite. In addition to providing criteria for use in identification, comparison of the *x*-ray diffraction measurements agrees with previous *x*-ray work in pointing toward a more consistent classification of pyroxenes and amphiboles when *x*-ray criteria are employed.

MAGNESIOSUSSEXITE, A NEW MINERAL FROM A MICHIGAN IRON MINE, ISOMORPHOUS WITH SUSSEXITE AND CAMSELLITE

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Two years ago Mr. A. L. Foss, at that time mining engineer at Ramsay, Michigan, sent the writer a specimen for identification. The exact occurrence of the specimen was given by Mr. Foss as a drift on the 25th level of the Eureka mine, Gogebic iron range. The mineral occurs as veinlets in the iron ore where the SiO_2 content gradually rises from 10 per cent to 30 per cent. The veins were discovered in the more siliceous ore.

The specimen is a part of a veinlet about $\frac{3}{4}$ of an inch wide as may be seen from the hematite attached on both sides. It is fibrous, though the fibers are hard without flexibility or elasticity. They are almost normal to the walls of the vein. The color is straw yellow to buff. The hardness is 3. The specific gravity is close to 2.83. Luster is dull to silky. Fusible at about 3 to a nearly black mass. It gives a boron green flame. Soluble in HCl giving a peculiar opalescent solution. A borax bead shows the presence of manganese.

The indices of refraction are $\alpha = 1.595 \pm .005$ and $\gamma = 1.660 \pm .005$. Birefringence about .065. Elongation $-$. Parallel extinction.

A complete chemical analysis (Table I) was made in the Rockefeller Rock Analysis Laboratory at the University of Minnesota, T. Kameda, analyst. The following paragraph gives a short description of the analytical methods used.

SiO_2, Fe_2O_3, $MgO + MnO$, and CaO were determined in one portion of the mineral. SiO_2 was separated in the usual manner by double evaporation with HCl. Before treating with HF, the SiO_2 was tested for, and found to be free from boron. The small amount of iron was separated from the silica filtrate by double precipitation with ammonia. Calcium, magnesium and manganese were then precipitated together as phosphates. The ignited precipitate of $Ca_3(PO_4)_2$, $Mg_2P_2O_7$, and $Mn_2P_2O_7$ were weighed, dissolved in sulphuric acid, and treated with alcohol to precipitate $CaSO_4$. The $CaSO_4$ was filtered off, reprecipitated as oxalate and ignited to CaO. The manganese was determined in a separate portion, after removal of silica and iron, by precipitation as MnS, followed by precipitation as the phosphate and ignition to $Mn_2P_2O_7$. The com-

TABLE I

CHEMICAL AND PHYSICAL PROPERTIES OF CAMSELLITE, MAGNESIOSUSSEXITE AND SUSSEXITE

Composition	Camsellite*	Magnesiosussexite	Sussexite**
MgO	45.24	29.32	16.29
MnO	1.09	23.48	37.58
FeO	1.28		
ZnO	none	none	3.87
Fe_2O_3	0.85	0.34	0.60
Al_2O_3	0.29		
B_2O_3	40.40	36.18	33.16 (diff.)
$H_2O+110°$	10.55	10.18	7.80
$H_2O-110°$	0.26	0.22	0.10
SiO_2	—*	0.43	0.50
CaO	—*	0.05	0.10
K_2O	0.04	none	
Na_2O		none	
P		none	
	100.00	100.20	100.00

Optical data			
Indices:	$\alpha=1.575\pm.005$ $\gamma=1.649\pm.005$	$1.595\pm.005$ $1.660\pm.005$	$1.639\pm.003$ $1.704\pm.003$
Elongation	—	—	—
Hardness	3−	3	3
Spec. Grav.	2.60?	2.83	3.12
Color	white	buff to yellow	buff to yellow
Structure	fibrous	fibrous	fibrous
Soluble in	HCl	HCl	HCl

* The analysis of camsellite was recalculated by Ellsworth and Poitevin. They found considerable amounts of silica and calcite in the original analysis, *op. cit.*

** Analysis by Poitevin and Ellsworth, *op. cit.*, p. 189.

bined weight of the manganese and calcium phosphates was deducted from the weight of the mixed phosphates to give the amount of $Mg_2P_2O_7$. Boron was determined in a separate portion by Chapin's distillation method.

The small amounts of SiO_2, Fe_2O_3, CaO and H_2O- are regarded as impurities. A recalculated analysis gives the following molecular proportions if Mg and Mn are considered to be isomorphous,

TABLE II

X-RAY DIFFRACTION MEASUREMENTS ON POWDERS OF CAMSELLITE, MAGNESIOSUSSEXITE AND SUSSEXITE

No.	Camsellite		Magnesiosussexite		Sussexite	
	Film mm.	I*	Film mm.	I	Film mm.	I
1	14.20	vs	14.20	m	14.15	m
2	17.15	m				
3	27.50	m				
4	29.70	m				
5	31.70	m				
6	33.70	vs	33.45	m	33.05	m
7	35.30	vs	34.95	w	34.45	w
8	37.05	s	36.85	m	36.60	m
9	38.90	s				
10	40.90	vs	40.60	w	40.15	vw
11	43.50	s	43.20	w	43.00	vw
12	45.35	s	45.15	vw	44.65	vw
13	46.95	w	47.10	vw		
14	51.10	m				
15	52.85	m	52.40	vw	51.70	w
16	54.15	w				
17	57.20	m	56.75	vw		
18	59.65	s	58.75	vw		
19	61.10	m			60.10	vw
20	62.00	m	61.50	w	61.50	vw
21	62.90	w				
22	65.40	vw				
23	67.95	w	67.90	vw		
24	70.65	m	70.10	vw		
25	73.05	w				

* Intensities.
vs = very strong
s = strong
m = medium
w = weak
vw = very weak

$2(Mg, Mn)O:B_2O_3:H_2O = 2.000:0.976:1.069$. The theoretical formula of the mineral, therefore, is $2(Mg, Mn)O \cdot B_2O_3 \cdot H_2O$.

A comparison of this new mineral with sussexite from Franklin Furnace, New Jersey,[1] and camsellite from its type locality in

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[1] Poitevin and Ellsworth, New optical data for analyzed sussexite: *Am. Mineralogist*, vol. 9, p. 199, 1924.

British Columbia,[2] shows a close relationship of the three. Their chemical and physical properties have been listed in Table I. Camsellite has also been described by Eakle[3] from California. Eakle claims that SiO_2 replaces a part of B_2O_3.

In order to be certain regarding isomorphism of these minerals x-ray powder diagrams were made. A circular camera with a radius of 57.3 mm. and Cu radiation ($K_\alpha = 1.537Å$) were used. The diameters of the samples were about 0.6 mm. Distances in the films were read from the outer edge of one line to the outer edge of the corresponding line on the other side of the zero beam. The measurements given in Table II, however, are the distances as they would have been if read from the zero beam to the outer edges of the lines. A correction for the diameter of the samples was also applied.

There is an abundance of lines in the film of camsellite. The other two minerals give only relatively few and weak reflections though taken under the same conditions. It is possible that the large amount of manganese in these minerals absorbs most of the Cu radiation emitted by the x-ray tube. The agreement of the three powder diagrams is satisfactory, however, when the following points are considered:

1. Due to the substitution of the larger manganese atom for magnesium the dimensions of the space lattices increase. The distances therefore measured in the films decrease correspondingly.
2. Since the minerals probably have relatively low symmetry (orthorhombic?), the magnitude of the expansion depends on the direction just as in the case of any other vector property of a crystal.
3. On account of the greater absorption of the diffracted x-ray energy in magnesiosussexite and sussexite only those lines correponding to relatively strong lines in camsellite are recorded in the films. The weak lines of camsellite have no equivalent in the other minerals.

CONCLUSIONS

Magnesiosussexite is the name of a new borate mineral from a deep iron mine of the Gogebic range in Michigan. The composition of the mineral, $2(Mg, Mn)O \cdot B_2O_3 \cdot H_2O$, places it between sussexite and camsellite with which it forms an isomorphous series. Judging by its composition, occurrence and relationship to the end members of this series it is probably hydrothermal in origin. As all these minerals are relatively inconspicuous and resemble other common fibrous aggregates of minerals they are probably much more common than reported. Incidentally this is not the first notice of a borate mineral from an iron mine in Michigan. Seamanite,[4] a phosphoborate of manganese was reported two years ago from the Chicagon mine on the Iron River range. The circulation in the iron ores of solutions containing boron is suggestive of hydrothermal leaching of silica from the ores, an hypothesis proposed recently by the writer.[5] In conclusion the writer wishes to thank Dr. H. V. Ellsworth for a specimen of camsellite used in this investigation.

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CHALCOPYRITE AND PYRRHOTITE INCLUSIONS IN SPHALERITE

PHILIP J. SHENON[1]

Numerous investigators have described inclusions of chalcopyrite and pyrrhotite in sphalerite. Some explain them as having been formed by replacement whereas others believe they are due to unmixing from a solid solution. The writer has recently studied thin sections and polished surfaces of ores from the Cowboy Mine in southwestern Oregon and, for the ores studied, has reached the conclusion that laths and blebs of pyrrhotite have formed in sphalerite by replacement, whereas chalcopyrite inclusions in sphalerite have formed by exsolution.

Teas[2] examined a large number of specimens of sphalerite showing inclusions of chalcopyrite and from his study concluded that the chalcopyrite had replaced sphalerite. Newhouse[3] described inclusions of chalcopyrite in sphalerite that appear to be definitely related to veinlets of chalcopyrite cutting the sphalerite and Lasky[4] found swarms of tiny inclusions of chalcopyrite in sphalerite close to contacts with other minerals which he believed were formed by replacement. Schneiderhöhn[5] and Van der Veen,[6] on the other hand, favor the theory of unmixing. Van der Veen has called attention to an example showing inclusions of chalcopyrite and of pyrrhotite oriented along cleavage directions and twinning planes in sphalerite which he described as the result of segregation from a solid solution of $ZnS.xCuFeS_2 \cdot yFeS$. Schwartz[7] heated sphalerite with inclusions of chalcopyrite for three days at various temperatures without dissolving the chalcopyrite and concluded that for the present it seems that the specimens showing inclusions (of chalcopyrite) which lack relationships to veinlets or to grain boundaries may be doubtfully considered to result from unmixing.

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[1] Published by permission of the Director of the U. S. Geological Survey.

[2] Teas, L. P., The relation of sphalerite to other sulphides in ores: *Trans. A. I. M. E.*, vol. **49**, pp. 62–82, 1918.

[3] Newhouse, W. H., An examination as to the intergrowth of certain minerals: *Econ. Geol.*, vol. **21**, pp. 68–70, 1926.

[4] Lasky, S. G., in Loughlin, G. F., and others, Geology and ore deposits of the Magdalena Mining district, New Mexico: In preparation by U. S. Geological Survey.

[5] Schneiderhöhn, H., Entmischungserscheinungen innhalb von Erzmischkristallen, etc.: *Metal. und Erz.*, vol. **19**, p. 68, 1922.

[6] Van der Veen, R. W., Mineragraphy and ore-deposition, p. 46, Figs. 18 and 19, 1925. The Hauge-G. Naeff.

[7] Schwartz, G. M., Textures due to unmixing of solid solutions: *Econ. Geol.*, vol. **26**, p. 758, 1931.

The Cowboy mine is located near Takilma, Josephine County, Oregon. The ore, consisting chiefly of sulphides, forms a series of slightly curved lenslike bodies in serpentine near the contact with fine grained greenstone. Below a depth of 50 feet the ore minerals are almost entirely hypogene. The abundant hypogene sulphides are chalcopyrite, cubanite, pyrrhotite, sphalerite, and cobaltite. Chalcocite occurs as a supergene sulphide and malachite, limonite, hematite, cuprite, and tenorite, are the more common oxidation products. The gangue minerals are serpentine, calcite, quartz, and epidote. The succession in the formation of the minerals was: serpentine, calcite, epidote, quartz, cobaltite, sphalerite, chalcopyrite and cubanite, pyrrhotite, sphalerite, and calcite. The succession was thrice interrupted by fracturing; once after the deposition of the gangue minerals, again after the deposition of cobaltite, and again after the deposition of the sulphides but before the introduc-

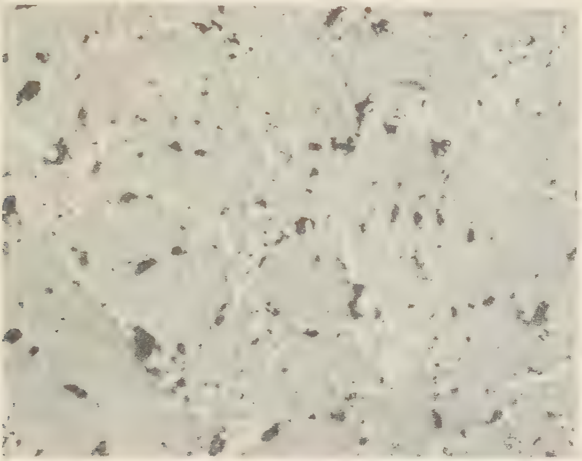

FIG. 1. Pyrrhotite (white) replacing sphalerite (gray) along grain boundaries and cleavage directions. Some of the tiny inclusions (white) oriented along cleavage directions are chalcopyrite. Black spots are holes. Nicols not crossed. Magnification 100 diameters.

tion of the younger calcite. Sphalerite occurs twice in the succession, once after cobaltite and again following pyrrhotite. The late sphalerite, since it follows pyrrhotite late in the series, probably indicates a recurrence of higher temperature conditions. Both generations of sphalerite are similar in appearance and both contain blebs of chalcopyrite, and the older sphalerite, where pyrrhotite is known to be replacing it, contains oriented laths and blebs of pyrrhotite; elsewhere the older sphalerite contains only inclusions of chalcopyrite. Some areas of the older sphalerite have been completely replaced by pyrrhotite with gradations into other areas where it is only partly replaced, principally along grain boundaries and cleavage directions (Fig. 1). Here in addition to the laths and blebs of pyrrhotite, the unreplaced sphalerite contains inclusions of chalcopyrite in about their usual abundance. In places remnants of the older sphalerite have been almost entirely replaced by chalcopyrite, but again there apparently is no increase in the number of chalcopyrite inclusions in the sphalerite remnants even next to veinlets of chalcopyrite (Fig. 2).

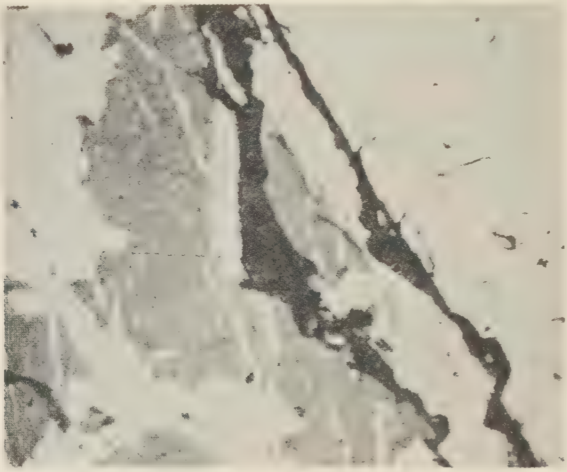

Fig. 2. Older sphalerite (gray), containing chalcopyrite blebs (white), partly replaced by chalcopyrite. Black spots are holes. Nicols not crossed. Magnification 400 diameters.

The younger sphalerite everywhere contains inclusions of chalcopyrite but none of pyrrhotite. Veinlets of it cut across contacts of pyrrhotite and chalcopyrite and no change in the number or arrangements of chalcopyrite inclusions is evident on either side of the contacts (Fig. 3). Some areas of younger sphalerite related to irregular fractures are surrounded by pyrrhotite and elsewhere by chalcopyrite, and in both associations the number and arrangement of inclusions of chalcopyrite are similar.

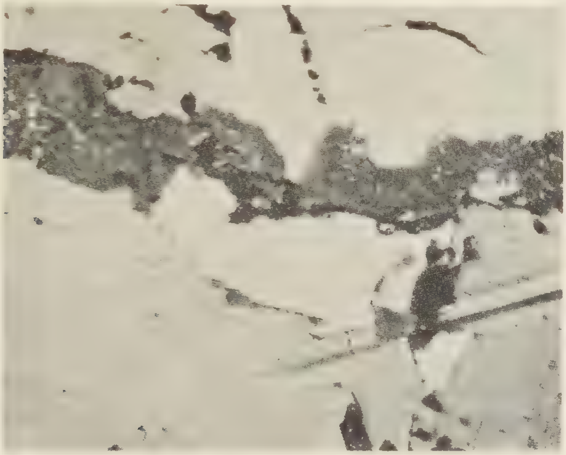

Fig. 3. Veinlet of younger sphalerite (dark gray) with inclusions of chalcopyrite (white) crossing chalcopyrite (white) and pyrrhotite (light gray). Nicols not crossed. Magnification 400 diameters.

SUMMARY

1. Since oriented laths and blebs of pyrrhotite occur in sphalerite only where pyrrhotite is known to be replacing sphalerite, the laths and blebs are believed to have been formed by replacement.

2. Inclusions of chalcopyrite occur in about equal abundance in both the older and the younger sphalerite. There is no apparent increase or decrease in the number of inclusions of chalcopyrite where different minerals replace the older sphalerite and, in addition, there is no apparent increase in the number of inclusions of chalcopyrite next to veinlets of chalcopyrite cutting the sphalerite. Therefore, in the ores under consideration, the inclusions of chalcopyrite are believed to have formed by some process of unmixing.

3. Where the younger sphalerite replaces pyrrhotite, the younger sphalerite contains as many inclusions of chalcopyrite as where it

replaces chalcopyrite. Therefore, in the ores studied, the number of inclusions of chalcopyrite has apparently not been influenced to a noticeable degree by the host mineral.

ACKNOWLEDGMENTS

The writer wishes to thank G. F. Loughlin and Waldemar Schaller of the United States Geological Survey for their suggestions and criticisms during the preparation of this paper.

HEAVY MINERALS OF THE COASTAL PLAIN OF MARYLAND

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The Coastal Plain of Maryland and contiguous states has been almost neglected by workers in sedimentary petrology. The one notable exception to this statement is furnished by Goldman's work on the Upper Cretaceous.[1] Wentworth and Campbell have considered, in a general way, the mode of formation of the Pleistocene terraces, omitting, however, any account of the heavy minerals contained therein.[2]

Lately, there have appeared two papers, one of which has for its purpose the description of minerals of the coastal terraces of Virginia (based on Wentworth's collections),[3] and another which makes passing reference to the mineralogy of the Eocene greensands of Virginia.[4] The present author wishes to animadvert on certain conclusions and methods found in these two papers, and to show the bearing on the problem of results attained in studying Maryland deposits of the same age. It is hoped that these results may be published in much greater detail later.

Eocene: Gunnell and Wilgus describe a modern beach glauconitic sand, confusingly said to have been collected from a shore bluff in the Aquia formation.[5] Their percentages show not a single typical heavy mineral, other than "ores," present. Glauconite, which may sometimes fall into the category of heavy minerals, composes 40 per cent of the sample.

The writer has examined ten samples of the Eocene from parts of southern Maryland adjacent to Virginia. The heavy mineral content of these samples is remarkably consistent in its general character, and may be averaged, for this purpose, as follows:

(Opaques—very large percentage,—not considered)

Zircon	35%
Staurolite	30%
Garnet	8%
Rutile	8%
Epidote	7%
Tourmaline	6%
Kyanite	3%
Chloritoid	2%
Sillimanite	1%

In addition, there are found occasional grains of andalusite, corundum, topaz, brookite, dumortierite, monazite, glaucophane, anatase, zoisite, titanite, muscovite, chlorite, hypersthene (?), and clinozoisite (?).

Gildersleeve states that, "The minerals commonly associated with glauconite in order of their importance are: quartz, feldspar, hornblende, magnetite, augite, zircon, epidote, tourmaline, garnet, and other minerals in smaller amounts."[6] This statement, as it stands, has little meaning. To be sure, these minerals, as common heavy minerals, probably are associated with glauconite, but their relative importance in the glauconite-bearing sediments of the world must be based on more than a statement, since local conditions will doubtless alter such proportions to a great degree. It should be noted, also, that staurolite is absent from the list cited, whereas in the Eocene greensands of Maryland this mineral is next in frequency after quartz, opaques (ilmenite and hematite) and zircon.

Considering the two papers cited, the following summation may be made with respect to Eocene heavy minerals:

(1) If the sample (No. 1738) of Gunnell and Wilgus came from the Aquia formation (Eocene), or, if the modern beach glauconitic sand is supposed to give some clue to the beds from which it is said to be derived, then, in either case, the composition of the Virginia greensands is essentially different from that found for the same beds a few miles away in Maryland.

(2) That Gildersleeve's statement as to minerals associated with glauconite has no evident basis in fact.

Miocene: To the writer's knowledge no one has enumerated or described heavy minerals from the Miocene of Maryland or nearby states. It is almost a reprehensible act to submit a list of minerals without giving the stratigraphy which has been worked out. Only to complete the sequence from Upper Cretaceous to Pleistocene (to be spoken of in the following section) is the subjacent table submitted. The percentages are averages, used to give a general picture, only:

CALVERT FORMATION; 70 samples:

Zircon	50%
Staurolite	15%
Garnet	10%
Epidote	10%
Tourmaline	5%
Sillimanite	5%
Rutile	2%
Kyanite	2%
Chloritoid	1%

CHAPTANK FORMATION: 5 samples showing essentially the same composition.

ST. MARY'S FORMATION: one sample, only, showing about 15% hornblende, and otherwise essentially the same minerals.

Pleistocene: The writer has examined but two samples from Pleistocene terraces in Maryland. Gunnell and Wilgus present the analyses of 16 samples from these formations in Virginia. Comment on their results may be best taken up as a study of the methods they have employed. Methods: (1) The 16 samples mentioned above were studied from grade sizes obtained in mechanical analysis. The distribution in fractions is as follows:

No. of samples	Grade size(s)
2	−1/16 mm.
6	+1/16 mm.
5	+1/8 mm.
1	−1/16, +1/8 mm.
1	+1/16, +1/8 mm.
1	+1/16, +1/8, +1/4 mm.

It is obvious from this table that, granted the possibility of variation of proportions with grade size (an actual occurrence in some known cases),[7] then the samples of different grade sizes cannot be compared with one another.

(2) One sample, only, was concentrated with heavy liquids. All are said to be "natural concentrates" and, hence, are not representative of the formation in which they are found.

(3) Failure to eliminate quartz by heavy liquids leaves that mineral present in such large quantities as to obscure rarer species of heavy minerals. This fact may explain the paucity of species in

many samples. In addition, such results cannot be compared with those of other workers, who uniformly separate off the "light" constituents.

(4) The method of estimating percentages is of doubtful value in correlation.[8]

The writer has attempted two tasks: (1) to prevent mistaken judgement of the heavy mineral content of certain formations; (2) to call attention to certain methods which render worthless results attained by tedious labour.

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[5] *Op. cit.*, pp. 62, 68.

[6] *Op. cit.*, p. 98.

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[8] Dryden, A. L., Jr., Accuracy in Percentage Representation of Heavy Mineral Frequencies: *Proc. Nat. Acad. Sci.*, vol. **17**, no. 5, 1931.

GARNET AS AN AMYGDULE MINERAL[1,2]

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U. S. Geological Survey, Golden, Colorado.

INTRODUCTION

Garnet has been found as a contact metamorphic mineral in the amygdules of andesite in the lava flows of the San Juan Mountains of southwestern Colorado. It is believed that this is the first recorded American occurrence, though several analogous ones in the British Isles have been on record for a number of years.

The presence of garnet in the lava flows surrounding the Mt. Sneffels intrusive stock, about five miles southwest of Ouray, was discovered by W. S. Burbank and the writer in the course of a detailed study of the geology and ore deposits of the Ouray mining district. The project was a part of the cooperative program carried on by the State of Colorado, the Colorado Metal Mining Fund, and the U. S. Geological Survey. The writer wishes to express his appreciation to Mr. Burbank for helpful suggestions in both field and laboratory.

THE HOST ROCK

The rocks in the immediate vicinity of the Mt. Sneffels stock consist of a thick accumulation of volcanic flows, breccias, and tuffs which range from rhyolite to andesite in composition. These have been subdivided into three formations[3] of which the intermediate, or Silverton Series of Miocene age is composed essentially of andesitic and latitic flows and flow breccias. The pyroxene andesite of this series is the only rock that has been found to contain garnet. In its original condition the rock was rich in labradorite, with much less pale green augite, hypersthene, orthoclase, and quartz, and still less magnetite. It was considerably altered, how-

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[1] Read before the Mineralogical Society at Tulsa, Oklahoma, December 30, 1931.

[2] Published by permission of the Director, U. S. Geological Survey, the Colorado State Geological Survey Board, and the Colorado Metal Mining Fund.

[3] For detailed discussions of the geology, see the following:

Whitman Cross, *U. S. Geol. Survey, Geol. Atlas, Telluride Folio,* (no. 57), **1899.**

Whitman Cross and Ernest Howe, *U. S. Geol. Survey, Geol. Atlas,* Silverton Folio, (no. 120), **1905.**

W. S. Burbank, Revision of geologic structure and stratigraphy in Ouray district of Colo.: *Proc. Colo. Sci. Soc.,* **12,** no. 6, 1930.

ever, by hydrothermal processes at about the time of the consolidation of the lava flows. Sericite, calcite, and chlorite were the chief products of alteration, and the hypersthene was almost entirely changed to serpentine.

The vesicles, which were abundant in several of the andesite flows, were partly filled with chlorite, quartz, calcite, and locally opal, chalcedony, barite, and magnetite during the same general period of alteration. Chlorite was the first mineral to form, lining the amygdules as aggregates of minute crystals which invariably show the anomalous "ultra-blue" interference color characteristic of the variety penninite. Two generations of quartz succeeded the chlorite. The first of these formed prisms laid parallel to the walls of the amygdules, while singly terminated prisms radiating from the walls were formed during the second generation. Calcite was the last mineral of importance to form in the amygdules and partly or completely fills the cavities. It is either massive or forms well-developed but simple rhombohedra or scalenohedra.

CONTACT METAMORPHISM

The nearly horizontal volcanic formations were intruded by the Mt. Sneffels gabbro-diorite stock, which caused the epidotization of the andesites and alteration of the original contents of the amygdules. The lavas for a distance of at least several thousand feet about the borders of the stock were considerably altered to epidote, which partly replaced practically all of the original minerals. Metamorphosed amygdules were found only on the northeast side of Mt. Sneffels, and never more than 1500 feet from the intrusive body. No minerals were developed in the non-amygdaloidal vesicles as a result of the contact metamorphic processes.

The metamorphosed amygdules are on casual examination similar to the original amygdules in that they are largely filled with chlorite, quartz, and calcite, but closer inspection reveals the presence of rather large numbers of crystals of garnet and of epidote. Garnet is embedded in both quartz and calcite, or projects as facetted crystals into the cavities. The crystals, with a maximum observed diameter of 3 millimeters, are invariably trapezohedra. This form is commonly striated, sometimes coarsely, by combination with the rhombic dodecahedron. Most of the crystals are clear yellowish-brown, others are green or light yellow. In thin section the garnet is light yellowish-brown and completely isotropic. The crystals are somewhat cracked, but zonal structure and inclusions are absent. The indices of refraction of two specimens, as determined by Miss J. J. Glass of the U. S. Geol. Survey, are 1.895 and 1.900, showing that the garnet corresponds closely in composition to the pure lime-iron variety, andradite.

Garnet was the first mineral to form in the amygdaloidal cavities as a result of contact metamorphism. It replaced quartz only slightly, but formed anhedral masses which filled the interstices between prisms of quartz. (See Figure 1.) Hexagonal outlines of crystals of quartz are usually sharply preserved by interstitial masses of garnet, but occasionally show some corrosion by the garnet. Calcite, which also occurred interstitial to quartz, was readily replaced by the garnet. Wherever found in contact with calcite the garnet shows rounded or subhedral outlines in contrast to the irregular masses between crystals of quartz which depended almost entirely on the enclosing material for their form. Definite evidence of replacement of calcite by garnet is for the most part lacking in the thin sections examined, but reasoning based on field evidence, where it is known that calcite had been formed long before the igneous intrusion that caused the formation of garnet, strongly suggests that the garnet found in calcite was developed by replacement of that mineral. The similarity in occurrence of masses of

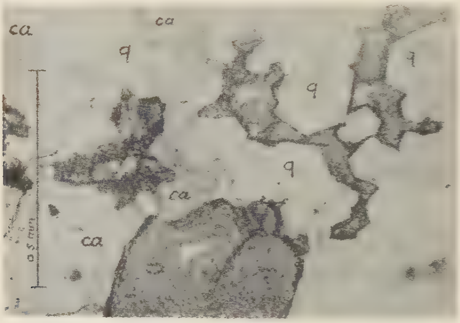

Fig. 1. Garnet (gr) and calcite (ca) interstitial to early quartz (q). The hexagonal outlines of prisms of quartz are in general sharply defined but occasionally show slight rounding and corrosion by the garnet. The interstitial masses of garnet may have filled open spaces among crystals of quartz or may have replaced calcite. Definite evidence of replacement of calcite by garnet is generally lacking in thin sections, but field evidence shows garnet to be later. A small amount of epidote (ep) is developed along cracks in calcite. Plain transmitted light. ×68.

garnet and calcite interstitial to quartz, well shown in Fig. 1, furnishes strong presumptive evidence of replacement of calcite by garnet. Facetted crystals apparently developed only in open spaces. Garnet has not been found in the body of the andesite.

Light green epidote succeeded and partly replaced the garnet. It occurs as crystalline aggregates or as groups of slender prismatic crystals several millimeters in length. Garnet is almost invariably corroded where in contact with epidote and in some places the garnet grains are almost completely replaced by it, as shown in Fig. 2. In addition to its rather vigorous attack on the garnet, epidote replaced calcite in the amygdules (Fig. 1), filled cracks and other openings, and partly replaced the constituent minerals of the andesite. Its formation was the most thorough and far reaching effect of the intrusion.

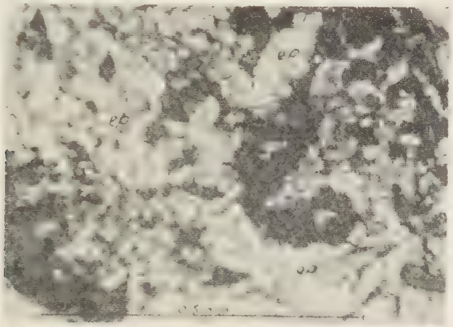

FIG. 2. Crystals of garnet (gr) largely replaced by crystalline aggregate of epidote (ep). Nicols nearly crossed. ×93.

In a period following that of epidotization, actinolite and quartz were formed at the expense of the earlier minerals. Actinolite has been observed only as microscopic needles enclosed in quartz, to which it imparts the porcelainic appearance characteristic of the late or contact-metamorphic quartz. The actinolite needles are too small to enable determination of all their optical properties, but the faint green color and pleochroism of the largest needles serve to identify the mineral as actinolite rather than tremolite. Much of the quartz-actinolite intergrowth, whose components probably formed almost simultaneously, was developed in open spaces, as is shown by the fact that masses of garnet, which are rounded and corroded by the intergrowth, often preserve distinct evidence of crystal outline. As facetted crystals of garnet only formed in open spaces it seems probable that the quartz-actinolite intergrowth filled remaining cavities and partly replaced such euhedral or subhedral crystals rather than that it was developed by replacement of residual calcite, in which the garnet never assumed crystal form. The relation of the intergrowth to garnet is shown in Figure 3.

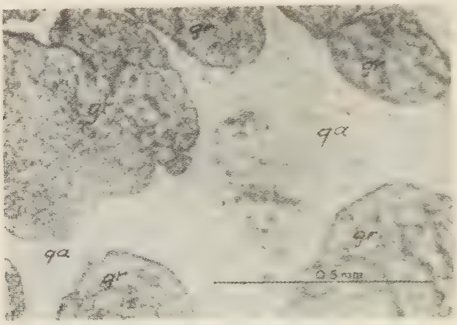

Fig. 3. Garnet (gr) partly replaced by late (contact metamorphic) quartz-actinolite intergrowth (qa). The individual masses of garnet are rounded residua of subhedral crystals which were corroded by the quartz-actinolite intergrowth. The mass of garnet in the lower right hand corner preserves some corroded but recognizable crystal faces. Plain transmitted light. ×68.

The individual masses of garnet are rounded residua of facetted crystals which were corroded by the intergrowth. Most of the crystals in the photograph are too much corroded to show crystalline form, but that in the lower right hand corner preserves some recognizable crystal faces. Occasionally the late intergrowth filled cracks in crystals of garnet or partly replaced irregular veinlets of epidote cutting garnet.

Albite and prehnite have been found in some of the amygdules. It can be stated with some assurance that they are products of the contact metamorphism, but data are insufficient to place them properly in the sequence of deposition. Albite appears to be earlier than epidote, but has not been observed in contact with garnet.

Significance of the Occurrence

A number of interesting problems are suggested by the occurrences described above, and although their complete solution must wait further data, several tentative conclusions can be drawn that may be of value in studies of contact metamorphic processes. The metamorphism, though strong enough to produce such relatively high temperature minerals as garnet, epidote, and albite, in the amygdules, had but slight effect on the intruded rocks. The presence of easily replaceable calcite in the amygdules was probably largely responsible for this selective metamorphism. The composition of the intruding and intruded rocks was also a factor, as the gabbro-diorite of the Mt. Sneffels stock and the intruded pyroxene andesite are closely similar in composition and offered little opportunity for exchange of chemical elements. Furthermore, it is generally agreed that basic rocks seldom effect such extensive metamorphism as do more acidic ones.

A brief consideration of the possible temperature at which contact metamorphism took place may be of interest, although no definite data are available. It was shown by Merwin[4] and later accepted by Lindgren[5] that the anisotropic garnet of more typical contact metamorphic deposits was probably formed at a temperature below 800°. The lack of zonal structure and inclusions and the uniform isotropism of all the garnet examined suggest that it was formed under conditions different from those that obtain during the more usual types of contact metamorphism. Since none of the garnet is anisotropic the upper limit of temperature reached during the formation of the new minerals in the amygdules is indeterminable, but the absence of tridymite and the presence of low-iron actinolite, which is decomposed at 900°[6] imply that the temperature failed to exceed 800° appreciably.

Garnet apparently had a short range of stability as compared with that of epidote. It evidently depended upon calcite for its formation, but ceased to develop while considerable calcite remained unreplaced. It may be that the equilibrium relations between andradite and epidote were very sensitive, and that a slight change in physical conditions caused the cessation of garnet formation and the beginning of epidotization. The presence of alumina may also have been a controlling factor in the development of the two minerals. Its very high index of refraction shows that the

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garnet is a nearly pure lime-iron andradite, with no admixture of the lime-alumina, or grossularite, molecule.[7] Epidote, however, always contains alumina in considerable quantities. Since the presence of alumina in the epidote is the chief chemical difference between that mineral and the andradite, it seems reasonable to suppose that the beginning of introduction of alumina, either from alteration of the andesite or from the magmatic emanations, marked the end of stability for andradite.

Other Occurrences of Garnet in Igneous Rocks

Only a few of the known occurrences of garnet in the openings of igneous rocks are even remotely similar to the one that has been described. Perhaps the best known of such occurrences is that near Nathrop, Colorado, which was described by Cross.[8] Spessartite, topaz, and sanidine occur in the lithophysae of a rhyolite dike that cuts pre-Cambrian rocks. Many of the crystals of spessartite are of good size, and aside from its scientific interest the locality has attracted some attention as a source of gem material. Cross mentioned a similar occurrence at Silver Cliff, Colorado.[9] Garnet and topaz were found in the main rhyolite sheet near Silver Cliff in a lithophysal zone that overlies a zone notable for its content of large rhyolitic spherulites. According to Cross, however, the minerals in the lithophysae at both these localities were primary, having formed almost contemporaneously with the final consolidation of the host rocks. They present evidence of having been formed by sublimation, but cannot be connected with contact metamorphic processes.

Harker[10] has described an occurrence in England that is strikingly similar to that near Ouray. The intrusion of a granite mass into an olivine-free basalt, whose vesicles had previously been filled with chlorite, quartz, and calcite, caused extensive metamorphism of the rock and of the amygdules, in which grossularite, green hornblende, a colorless augite, epidote, and quartz were developed. With the exception of grossularite and quartz all these minerals entered the basalt, whose plagioclase phenocrysts and groundmass were entirely recrystallized during the metamorphism. An augite-andesite cut by the same granite was similarly altered, but because of its lower lime content few of the lime silicates were formed in it. Teall has described a similar occurrence in Scotland[11] where a lime-iron garnet and new feldspars were formed from the contents of the amygdules.

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[7] N. H. and A. N. Winchell, Elements of Optical Mineralogy, Part II, pp. 263–266, *New York*, **1927**.

[8] Whitman Cross, On the occurrence of topaz and garnet in lithophyses of rhyolite: *Am. Jour. Sci.*, (3) **31**, pp. 432–438, 1886.

[9] Whitman Cross, Geology of Silver Cliff and the Rosita Hills, Colo.: *U. S. Geol. Survey, Ann. Rept.*, **17**, pt. 2, pp. 263–403, 1896.

[10] Alfred Harker and J. E. Marr, Supplementary notes on the metamorphic rocks around the Shap granite: *Quart. Jour. Geol. Soc.*, London, **49**, pp. 360–364, 1893.

In both the British occurrences metamorphism was much more thorough than was that caused by the Mt. Sneffels stock near Ouray. This difference may have been due to the greater dissimilarity in composition of the intruding and the invaded rocks. In both occurrences the alteration of the amygdules extended farther from the intrusive body than did the alteration of the lavas themselves.

SUMMARY

Near Ouray, Colorado, the intrusion of a gabbro-diorite stock into a pyroxene andesite rock caused metamorphism of amygdules in the andesite. The new minerals developed partly by replacement of the original chlorite, quartz, and calcite of the amygdules, and partly by filling of open spaces. It is believed that the presence of calcite was largely responsible for the development of garnet. Comparison with analogous occurrences in the British Isles, where alteration of the amygdules was of minor importance as compared to the metamorphism of the rock itself, leads to the belief that the metamorphism at Ouray was of comparatively slight extent and of somewhat unusual character.

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[11] Teall, *Annual Report, Geol. Survey,* **1896,** p. 47.
Teall, *Memoirs, Geol. Survey;* Silurian Rocks of Scotland, pp. 647–650, **1899.**

THE REFRACTIVE INDICES OF BLOEDITE[1]

WALDEMAR T. SCHALLER, *U. S. Geological Survey.*

In the incomplete optical data for bloedite in the older reference books,[2] the refractive index β (the only one listed) is given as 1.500. Apparently the first complete determinations published are those of Stranetzky[3] who in 1907 gave the indices for lithium, sodium, and thallium light for simonyite (synonym for bloedite). Those for sodium light are: $\alpha = 1.4825$, $\beta = 1.4839$, $\gamma = 1.4866$. The axial angle calculated therefrom ($2V = 71°10'$) agrees with earlier measurements. Stranetzky states that γ is the acute bisectrix (ist die erste Mittellinie). From this statement, the mineral would be positive, as is also required by the relative position of β with respect to α and γ. There is no question as to the identity of simonyite with bloedite and as all other determinations give the optical sign of bloedite as negative, there is obviously an error in Stranetzky's determination of β and in his statement that γ is the acute bisectrix. That the mineral is optically negative was verified repeatedly by the writer and by his colleagues C. S. Ross and J. J. Fahey on material from Germany, Estancia Valley, New Mexico, and from San Luis Obispo County, California.[4]

Stranetzky's incorrect determination of β was reproduced in the International Critical Tables[5] although Goergey[6] had called attention to the error of taking γ as the acute bisectrix and had considered Stranetzky's determinations of refractive indices as not usable. However, only his β determination is in error; α and γ are probably correct as they are practically identical with later determinations. Goergey's own values are slightly in error.

In 1910, Goergey[7] gave the following values for sodium light:

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[1] Published by permission of the Director, U. S. Geological Survey.

[2] Dana's *System of Mineralogy*, **1892**, p. 947; Groth's *Chemische Krystallographie*, vol. **2**, 1908, p. 506.

[3] Stranetzky, Kajetan, Die optischen Eigenschaften des Simonyt von Hallstadt: *Mineral. u. petrogr. Mitth.*, vol. **26**, p. 144, 1907. The reference is omitted in Appendix II to Dana's *System of Mineralogy*, under bloedite (p. 16).

[4] This bloedite was described by the writer, Large crystals of bloedite: *U. S. Geol. Survey*, Bull. no. **610**, pp. 148–149, 1916.

[5] *Internat. Critical Tables*, vol. VII, **1930**, p. 27.

[6] Goergey, R., Zur Kenntniss der Minerale der Salzlagerstätten: *Mineral. u. petrogr. Mitth.*, vol. **29**, p. 207, 1910.

[7] Goergey, R., *loc. cit.*, p. 207.

$\alpha=1.486$, $\beta=1.488$, $\gamma=1.489$. These values were reproduced by Larsen.[8]

It was noticed in determining the refractive indices of saline minerals from the potash field of New Mexico and Texas, that there seemed to be a decided tendency for the determinations of Goergey to be slightly too high, about 0.003 to 0.004 on the average. Thus Goergey's values for some of the saline minerals are higher than the highest values determined by Schaller and Henderson[9] as follows:

TABLE SHOWING HOW MUCH HIGHER GOERGEY'S DETERMINATIONS OF REFRACTIVE INDICES OF SOME SALINE MINERALS ARE, AS COMPARED WITH THE HIGHEST VALUES DETERMINED BY SCHALLER AND HENDERSON. ALL THE DIFFERENCES GIVEN ARE IN ONE DIRECTION

Mineral	Bull. 833 U.S.G.S. page	α	β	γ
Glauberite	30	.002	.000	.001
Kieserite	41	.003	.004	.003
Langbeinite	43	...	.002	...
Leonite	46	.002	.004	.003
Polyhalite	72	.000	.001	.000
Bischofite	80	.003	.001	.009
Bloedite	80	.005	.005	.005
Thenardite	81	.005	.002	.000

The average difference is 0.003 and if Goergey's values for bloedite be reduced by this correction, they become: $\alpha=1.483$, $\beta=1.485$, $\gamma=1.486$. The reason for Goergey's high values probably lies in his use of such volatile constituents as benzol and alcohol in his immersion oils.

In 1929, Laszkiewicz[10] determined the refractive indices and dispersion for bloedite. His values for sodium light are: $\alpha=1.4826$,

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[8] Larsen, E. S., The microscopic determination of the non-opaque minerals: *U. S. Geol. Survey*, Bull. no. **679**, p. 243, 1921.

[9] Schaller, W. T., and Henderson, E. P., Mineralogy of drill cores from the potash field of New Mexico and Texas: *U. S. Geol. Survey*, Bull. no. **833**, 1932.

[10] Laszkiewicz, A., Bloedite from Kalucz: *Arch. Min. Soc. Sci. Varsovie*, vol. **5**, pp. 79–96, 1929. Abstracted in *Mineral Abstracts, Mineral. Mag.*, vol. **22**, p. 334, 1930.

$\beta = 1.4855$, $\gamma = 1.4869$. Schaller and Henderson[11] give the values: $\alpha = 1.481$, $\beta = 1.483$, $\gamma = 1.484$, stating that all indices were below 1.485 and that Goergey's figures are considered to be a little high.

All the values listed, with the exception of those of Stranetzky, agree in that bloedite is optically negative and where given, 2V is close to 71°. The optical properties of bloedite thus seem to be very constant, the slight variations in the third decimal being due to the investigators and not to any variation in the properties of the mineral.

In summarizing the determinations listed, with regard to the critical remarks given, namely that the value of β given by Stranetzky is in error and therefore is omitted and that Goergey's values are 0.003 too high and are lowered that amount, the refractive indices of bloedite are given as follows:

	α	β	γ
Stranetzky	1.4825	......	1.4866
Goergey (corrected)	1.483	1.485	1.486
Laszkiewicz	1.4826	1.4855	1.4869
Schaller and Henderson	1.481	1.483	1.484

New Determinations of the Refractive Indices of Bloedite

	α	β	γ
California Det. by C. S. Ross	1.483	1.486	1.487
California Det. by J. J. Fahey	1.483	1.486	1.487
Artificial Det. by Ross and Fahey	1.483	1.486	1.487
Germany Det. by Schaller	1.483−	1.485+	1.487
New Mexico Det. by Schaller	1.483	1.485+	1.487

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[11] Schaller, W. T. and Henderson, E. P., Mineralogy of drill cores from the potash field of New Mexico and Texas: *U. S. Geol. Survey*, Bull. no. **833**, p. 80, 1932.

Obviously, the slightly discordant values given by Schaller and Henderson are about 0.002 to 0.003 too low.

The writer therefore redetermined the indices of refraction of bloedite from Germany and from Estancia Valley, New Mexico, and enlisted the aid of his colleagues C. S. Ross and J. J. Fahey who independently made similar determinations on the bloedite from California and on artificial bloedite. All the determinations were made by the oil immersion method using artificial day light (white light).

Rounding off all determinations to three decimals, using the corrected values of Goergey, and replacing the published values for bloedite, given by Schaller and Henderson, by those just given, the indices of refraction of bloedite are as follows:

Refractive Indices of Bloedite

	α	β	γ
Germany, Stranetzky	1.483	.....	1.487
Germany, Goergey	1.483	1.485	1.486
Kalusz, Laszkiewicz	1.483	1.486	1.487
California, Ross	1.483	1.486	1.487
California, Fahey	1.483	1.486	1.487
Germany, Schaller	1.483	1.485	1.487
New Mexico, Schaller	1.483	1.485	1.487
Artificial, Ross and Fahey	1.483	1.486	1.487

The average of these determinations expressed to three decimals give as the refractive indices of bloedite: $\alpha = 1.483$, $\beta = 1.486$, $\gamma = 1.487$. The statement by Schaller and Henderson that all indices are below 1.485 is in error.

As indicated by the determinations of Stranetzky and Laszkiewicz, for sodium light, the α index lies between 1.4825 and 1.4830 and the γ index between 1.4865 and 1.4870. Averaging these two sets of determinations and using only the β value given by Laszkiewicz, the refractive indices for bloedite for sodium light, expressed in four decimals are: $\alpha = 1.4826$, $\beta = 1.4855$, $\gamma = 1.4868$, with an error of probably less than 0.0003.

NOTES AND NEWS

CASTANITE FROM CHUQUICAMATA, CHILE

Mark C. Bandy, *Chuquicamata, Chile.*

A very complete description of an occurrence of castanite was given in this journal, by Professor A. F. Rogers.[1] The material used by Professor Rogers came from Knoxville, California. The original material used by Darapsky[2] in establishing the mineral species, came from Sierra Gorda, near Chuquicamata. As stated by Professor Rogers in the introduction to his article, Linck[3] states that castanite is undoubtedly a synonym for amarantite ($Fe_2O_3 \cdot 2SO_3 \cdot 7H_2O$).

A study of the sulphate minerals at Chuquicamata is being made and it is believed that the following data on castanite from this locality would be of interest. Castanite occurs with amarantite and the two are easily distinguished as distinct mineral species.

Occurrence and Association of Castanite

Practically all of the oxide minerals at Chuquicamata have been formed under arid conditions and from solutions high in acid content. As a rule the solutions probably carried a high concentration of mineral salts. At present, it is only once or twice in a decade that sufficient moisture falls to dampen the ground more than six inches below the surface. It is certain that this condition has existed for a very long time. The elevation of the ground water in the vicinity of the mine varies greatly, both because of the nature of the rock and the steep topography. The ground water is encountered from 160 feet to over 600 feet below the surface.

The area in which the castanite is found is one of large, massive pyrite veins, which have been oxidized for a considerable distance below the surface. The castanite is almost entirely limited to the soft gossan of these veins and is rarely found in the intervening country rock. Judging from the present exposures of these veins, water percolating through them from the surface would become saturated with copper, and especially iron and earthy sulphates, within a very short vertical distance, and carry a considerable percentage of free acid.

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[1] *Am. Mineral.*, vol. **16,** 1931, pp. 396–404.

[2] *N. Jb. f. Min.*, **1890,** 2, pp. 267–269.

[3] Hintze's *Handbuch der Mineralogie,* I Band, **1929,** pp. 4426–4427.

Castanite has not been observed over 150 feet below the original surface of the ground. It is only found in the larger veins and is always associated with closely allied iron sulphates. All of the specimens so far obtained show the castanite in intimate association with amarantite. This association is so intimate that it was difficult to separate the two minerals for chemical analyses. The castanite occurs as round masses up to one inch in diameter within the amarantite, and in irregular, alternating bands with amarantite, surrounding pieces of wall rock within the vein.

Other iron sulphates that have been identified, which are closely but not intimately associated with the castanite are, copiapite, coquimbite, römerite, melanterite, pisanite, quenstedtite, fibroferrite and a mineral believed to be carphosiderite. Chalcanthite is usually associated with the castanite, while kröhnkite and copper bearing gypsum are less common associates.

The castanite consists of massive aggregates of very small, somewhat acicular, subhedral crystals. The largest crystal observed was a twin crystal, slightly under 0.9 mm. in length. The crystals are transparent, with some inclusions of an undetermined material. In the hand specimen the massive castanite is a splendent, burnt-orange mass. The color and effect of the castanite is heightened by the dull, opaque appearance of the associated amarantite. Within five minutes after exposure of a fresh face of a specimen, the amarantite is covered with a dull dehydration film. The individual crystals of the castanite, when placed on a piece of white paper, are a brilliant reddish-brown color.

There are no facilities available for determining any of the geometrical constants of the castanite crystals. Due to the very small size of the crystals and their subhedral character, it is doubtful if material suitable for crystallographic study could be obtained from any of the present occurrences at Chuquicamata. Castanite, as well as practically all of the other iron sulphates, shows partial solution of the crystal faces.

PHYSICAL PROPERTIES

All of the castanite observed has the same reddish-brown or burnt-orange color. The luster is vitreous and brilliant. Streak, yellow with a brownish tint. Powder, orange with a reddish tint. Hardness, 2.5. Taste, acid, astringent. Specific gravity was not determined. It is practically stable at room temperature but undergoes a slight dehydration in a few days time. This dehydration is no doubt due in great part to the extreme aridity of this locality.

CHEMICAL PROPERTIES

Castanite is slightly soluble in cold water, 20°C. In warm and hot water the castanite is soluble, with decomposition, yielding free sulphuric acid and precipitating basic iron salts. It is completely soluble in hydrochloric and nitric acids, and is partially soluble in sulphuric acid.

Chemical analyses by Mr. B. W. Carter gave the following results,

ANALYSES OF CASTANITE BY B. W. CARTER

	I*	II**
SiO_2	tr.	0.3
Al_2O_3	0	0.4
Fe_2O_3	34.1	31.4
FeO	0	0
CaO	tr.	0
MgO	tr.	0
$H_2O+100°C$	29.2	15.7
$H_2O-100°C$		13.1
CuO	0	3.9
MnO	0	0
SO_3	36.7	33.3
Cl	tr.	0
Ignition loss		2.2
Total	100.0	100.3

* I. Carefully picked sample of almost pure material. Water obtained by difference.

** II. Relatively impure sample.

Knoxville, Cal.		Chuquicamata, Chile II	I	Molecular Ratios I		Theoretical
Fe_2O_3	34.47	33.6	34.1	.214	1.00	34.58
SO_3	35.11	35.6	36.7	.459	2.15	34.58
H_2O	30.31	30.8	29.2	1.622	7.59	30.84

In the following table these analyses are compared with the analysis reported by Rogers.

It is of interest to note that the material from both localities is low in water and iron, and high in sulphur. The low percentage of water in the Chuquicamata material is unquestionably due in part to slight dehydration. Analysis No. II contained so much amarantite that there is too great an error in the figures given in the above table to be of use in deriving a formula

While the analysis given above, No. I, shows a low water ratio for castanite and would indicate a formula, $Fe_2O_3 \cdot 2SO_3 \cdot 7\frac{1}{2}H_2O$, it is believed that this is too low in water content and the formula as assigned to castanite by Darapsky,[4] $Fe_2O_3 \cdot 2SO_3 \cdot 8H_2O$, is correct.

PYROGNOSTIC TESTS

When castanite was heated in a closed tube at a low temperature, it gave off water which by analysis contained considerable free sulphuric acid. At higher temperatures SO_2 fumes were given off. During heating the castanite turned from a light orange color to brown, then reddish-brown and finally black. Upon ignition the castanite yielded a black, somewhat magnetic residue and lost, by weight, 64 per cent of its mass.

OPTICAL PROPERTIES

The following optical properties were determined. The crystals were negative. Pleochroism was fairly strong with N_g reddish brown and N_p light yellow. Dispersion was high with $\rho > v$. Chuquicamata material yields a slightly eccentric biaxial interference figure, as shown by Rogers for the Knoxville material. The indices of refraction as found by the immersion method are; N_p, 1.550 $\pm .005$; N_m, $1.645 \pm .005$; N_g, $1.660 \pm .005$. $N_g - N_p = 0.110 \pm .01$.

ORIGIN OF CASTANITE

From the occurrence and associations of castanite at Chuquicamata, Chile, it is believed that it is formed under conditions of low temperature. It probably crystallizes from solutions high in both ferric iron and free sulphuric acid. It forms at comparatively shallow depths, less than 150 feet at Chuquicamata, and probably at even shallower depths in less arid localities.

[4] *Op. cit.*

ARTIFICIAL THERMONATRITE

JOHN SVATIK AND EDWARD H. STEVENS, *University of Chicago.*

Crystals of Na_2CO_3 H_2O (artificial thermonatrite) were grown by James M. Bradford[1] from a water solution of Na_2CO_3 concentrated at 70°C and allowed to evaporate slowly at that temperature. Some of these were given to the writers for optical determinations.

The forms observed were: $\{001\}$, $\{110\}$, $\{100\}$, and one crystal showed a macrodome. The crystals are dominantly of two habits; $\{001\}$ tablets with elongation along the *b*-axis, and prismatic $\{110\}$ with the front pinacoid well developed. The former are first to appear, while growth along the *c*-direction progresses with time. The optical properties are in conformity with those obtained by Merwin ($X=b$), as cited by Winchell,[2] and not with those of Lacroix ($X=a$).

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[1] Department of Physics, University of Chicago.

[2] Winchell, A. N., The Microscopic Characters of Artificial Inorganic Solid Substances or Artificial Minerals, 2nd. Ed., New York, **1931,** p. 200.

PROCEEDINGS OF SOCIETIES

PHILADELPHIA MINERALOGICAL SOCIETY

Academy of Natural Sciences of Philadelphia, June 3, 1932.

A stated meeting of the Philadelphia Mineralogical Society was held on the above date with the president, Dr. Cajori, in the chair. Twenty-seven members and 33 visitors were present. Upon favorable recommendation of the council, Mr. George Vaux of Bryn Mawr, Penna., was elected a member. The chair announced the death of E. A. Groth in December, 1931.

Mr. Samuel G. Gordon addressed the society on "Greenland Minerals," largely descriptive of localities in southern Greenland visited in 1923, and illustrated by means of lantern slides.

Mr. Knabe exhibited specimens of pyrrhotite and limonite secured at Huntington Valley. Mr. Vanartsdalen described visits to Easton and Sayresville. Dr. Hawkins described white stilbite from the Long Island City water supply tunnels. Dr. Wherry exhibited a fossil pine cone from the black shales of Bucks County.

W. H. FLACK, *Secretary*

Academy of Natural Sciences of Philadelphia, September 8, 1932

Vice-president Toothaker presided at a stated meeting of the Society on the above date. Thirty-four members and twenty-two visitors were present. Mr. E. R.

Gudehus was proposed for membership. Upon favorable recommendation of the council Mr. Harold Philip was elected a junior member.

The following summer trips were reported by members: by Mr. William Knabe to the Gwyned Tunnel cut near North Wales, where he obtained pyrite, calcite, quartz, petrified wood, and a number of fossils. On a visit to the Mermaid Lane quarries he found tourmaline, garnet, torbernite, and muscovite. Mr. Vanartsdalen visited Lumberville, obtaining pyrite. Mr. Boyle and Mr. Arndt found limonite geodes and quartz crystals at Henderson Station. Mr. Morgan exhibited brown tourmaline from Sparta Junction, N. J., and quartz crystals from Newton, N. J.

Mr. Gordon described some collecting at a number of sodalite and cancrinite localities in the Bancroft area, Ontario, Canada. Sodalite of various colors, yellow, pink, and colorless cancrinite, black tourmaline in blue sodalite, garnet, natrolite, and corundum were among the finds. At Hybla ellsworthite, allanite, moonstone, amazonstone, and other minerals were obtained.

Mr. Toothaker exhibited a kunzite crystal from California purchased in Europe. Mr. Cienkowski described a trip to New England, New York and Ohio, exhibiting datolite from Westfield, quartz from Herkimer County, and fluorite from Clay Center.

Dr. Newcomet showed a new type of "micromount" which he had developed to permit examination of a specimen on both upper and lower sides.

W. H. FLACK, *Secretary*

BOOK REVIEW

A TEXTBOOK OF MINERALOGY, WITH AN EXTENDED TREATISE ON CRYSTALLOGRAPHY AND PHYSICAL MINERALOGY, Edward Salisbury Dana, fourth edition, revised and enlarged by William E. Ford, XI+851 pages, John Wiley & Sons, Inc., *New York*, **1932.** Price $5.50.

This new edition of "Dana's Textbook of Mineralogy" has been greatly enlarged as the text with appendices now covers 822 pages as compared with 693 pages in the third edition. While the main features of the previous edition have been retained there have been some notable changes and additions. Among these are a 17 page section on crystal structure. The usefulness of such a brief treatment of this important phase of crystallography seems very questionable to the reviewer.

The new part devoted to the origin, mode of occurrence and association of minerals is so condensed that even the most fundamental principles have been slighted. The few sketchy phase rule diagrams in this section are anything but illuminating. That for the binary system, SiO_2–Al_2O_3, is obsolete, apparently being based on the older work of Shepherd and Rankin which was revised in 1924 by Bowen and Greig. References to "The Data of Geochemistry," by F. W. Clarke, are to the third edition, 1916, although that work is now in its fifth edition.

The descriptive part has been enlarged to 385 pages, the arrangement and mode of presentation being kept the same as heretofore. It is stated in the preface that this part is intended to serve as a substitute for the "System of Mineralogy" pending its revision. At least a brief description of all known minerals is given and many doubtful species are also mentioned. The mineral index has been expanded to include a great number of foreign names. Notes on the structure and stability relations have been added to the descriptions of some minerals but these are for the most part concealed in paragraphs in small type and are not given the proper emphasis.

Full use has not been made always of modern research bearing on the formulas of minerals or the interpretation of mix-crystal series. This is particularly regrettable in the case of the amphiboles. Though the new amphibole formula is mentioned in the introduction to this group the old misleading metasilicate formulas are given with the descriptions of the individual species.

Throughout the remainder of the book there are few changes. Though an effort has been made to eliminate errors a number have been carried over from the previous edition. Whereas the description of the symmetry elements has been amplified by a mention (in small type) of alternating symmetry, the faulty statement of symmetry of the tetragonal tetartohedral class in the third edition, recently criticized by Tunell and Morey, has been copied without change.

On page 62 the following statement is taken from the previous edition. "The three figures [*uvw*] are said to be the symbol of the zone in question. They represent the reciprocals of the values of the three coordinates, or in other words are the indices of a point, P, on the zonal axis." The statement in the second sentence is not true. It may be corrected by omitting the words "the reciprocals of."

In spite of the errors and deficiencies "Dana's Textbook of Mineralogy" must still be considered without question as the outstanding text among English books in its field. It will doubtless continue to be the standard work of reference.

ADOLF PABST